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INCORPORATION OF GPS/INS INTO SMALL AUTONOMOUS UNDERWATER VEHICLE NAVIGATION

by

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Navigation of an Autonomous Underwater Vehicle (AUV) is a problem that has not been adequately solved. Although the inclusion of the Global Positioning System (GPS) into AUV navigation has been briefly examined before, this possibility is explored further in this thesis. GPS and Inertial Measurement System (INS) based navigation package offers many advantages for AUV navigation especially for transits and precise object location in shallow water.

This thesis provides background information on GPS and INS as they pertain to small AUV employment. Other required components are also examined as they pertain to small AUV employment. The use of the GPS/INS navigation package for AUV transits and precise object location work is presented. Two designs with specified components are developed. A GPS receiver was tested for AUV employment suitability. These test results are presented and analyzed.

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ABSTRACT

Navigation of an Autonomous Underwater Vehicle (AUV) is a problem that has not been adequately solved. Although the inclusion of the Global Positioning System (GPS) into AUV navigation has been briefly examined before, this possibility is explored further in this thesis. GPS and Inertial Measurement System (INS) based navigation package offers many advantages for AUV navigation especially for transits and precise object location in shallow water.

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I. INTRODUCTION

A. BACKGROUND

Navigation of an Autonomous Underwater Vehicle (AUV) is a problem that has not been adequately solved. Many methods of navigation of AUVs have been proposed and in some cases implemented. These have included the use of: gravity fields, sonar, and dead reckoning in conjunction with inertial navigation systems.

Although the inclusion of the Global Positioning System (GPS) into AUV navigation has been briefly examined before, this possibility should be explored further. GPS is a series of navigational satellites that provide world-wide positioning, altitude, course, and speed information. In fact, GPS provides the most accurate open ocean positioning information available.

Even though an AUV navigating with GPS has the disadvantage that it must surface or at least extend its GPS antenna into the air to obtain a GPS fix, this method is still worth employing in many applications such as shallow water operations and long range transits. GPS could also be coupled with other short range mission specific navigational methods for application in various stages of a mission. GPS may also provide an excellent method of determining the position of an object of interest. When an object of interest is located, a GPS fix may be taken at that time or the last GPS fix may be used to accurately record the position of the object. Inertial and other sensors might be used to carry the GPS position to the object of interest.

Off the self components and GPS single board receivers provide a way to build the small, low power systems required for AUV incorporation. Given the accuracy of GPS, its proven performance, small size and low power, a GPS navigational based system offers many advantages to AUV navigation and may solve the navigational problem for many AUV applications.

B. PURPOSE OF THIS THESIS

The purpose of this of this thesis is to explore the feasibility of integrating GPS capability into small AUV navigation with the use of an Inertial Navigation System (INS). This thesis will establish a set of physical and operational criteria of the GPS navigational package. It will present two operational scenarios and two hardware designs as examples of how GPS may be integrating with small AUV navigation. The components of the hardware designs will be examined independently and recommendations of individual components will be made. This thesis will present test data collected from a stationary GPS receiver under simulated AUV environment to determine the suitability of using GPS for AUV navigation in general. The other key component of this package is INS. An Inertial Navigation System for use in this package will be explored. Background information on INS and GPS will be provided.

C. THESIS ORGANIZATION

Chapter I is the introduction to this Thesis. Chapter II provides a survey of previous work in this area. Next the operational requirements for a Small AUV Navigational System (SANS) that incorporates GPS and INS or other internal guidance systems are established in Chapter III. The development platform that will serve as the test bed for the SANS system is also presented in Chapter III. Chapter IV and V provide important background information on GPS and INS respectively. In addition, the results from tests conducted on a stationary GPS receiver will be presented in Chapter IV. The purpose of these tests was to determine the suitability of using GPS for AUV navigation. An INS system will also be selected for incorporation into the SANS package in Chapter V. Chapter VI presents the requirements for the other hardware components and the selections of the individual components. The power requirements and analysis for the SANS are also presented in Chapter VI. The integration of the different components and the system configurations are

presented in Chapter VII. Conclusions and future work are presented in Chapter VIII respectively.

II. SURVEY OF PREVIOUS WORK

A. AUV NAVIGATION

Most of the previous approaches to navigating of AUVs fall into two different categories: sensor based navigation and external signal based navigation. Sensor based navigation refers to an AUV navigational system that is self contained, using only data collected in real time by onboard senors and/or pre-stored information. These sensors provide information about the natural environment around an AUV. The most common sensors for sensor based navigation are sonar and vision sensors.

Sonar systems are primarily used in one of two ways: guidance sonars and speed measuring sonars [HUTC 90], [STEV 90], [HUTC 90]. In order to effectively use a sonar guidance system, significant a priori knowledge of the environment is required. Basically, the AUV on board computer attempts to match the sonar information to stored geographical data in a terrain guidance or natural boundaries[CAMP 91] method to determine its position. The same approach and a priori knowledge requirements applies to vision guidance systems. Speed measuring sonars include correlation and doppler sonar. Here, the sonar determines the AUV speed via a ground locked mode, and this information is used to aid in dead reckoning. The reason for the use of sonar in determining speed is that it will provide AUV speed relative to the earth. Other methods such as propeller speed measurements and water speed measurements are affected by such factors as currents.

Another sensor based navigation method that requires a priori knowledge is a Gravity Gradiometer Navigation System(GGNS) [JIRC 90]. This system uses gravity gradient sensors. The measured gravity gradients are compared with mapped values to determine AUV position.

Once the information from the sensors has been processed, it then may be used to assist an inertial navigational system (INS). Of the two types of inertial navigational

systems, stable platform and strap down, only strap down provides a viable option for typical small AUV employment. Stable platform systems are generally too large and require too much power to be reasonably employed in AUV's [MCGH 92].

External signal based components receive some type of external navigational signal not natural to the AUV environment. Such systems may include radio beacons, sonar beacons, transponders, Loran, Omega, Navsat, and of course GPS.

Sonar beacons, radio beacons and transponder trackers rely on close range transmitters. These transmitters must be in place before the AUV mission or put in place by the AUV. These are only good for short range navigation.

Loran and Omega are long range radio navigation systems. The major disadvantage of the Loran system is that it does not provide worldwide coverage. Although Omega [MALO 85] does provide worldwide coverage, it has undesirable characteristics for AUV employment. If the signal reception is interrupted, the Omega receiver has to be reinitialized. This makes it undesirable for AUV employment due to loss of signal when submerged and due to power drain. In addition, the best accuracy Omega offers is one to two nautical miles in its worldwide coverage. Navsat [MALO 85] is a satellite based navigation system that will be turned off sometime shortly after GPS 3-D worldwide coverage is complete. It provides fixes only every few hours. Loran is not expected to continue much past the year 2000 [MALO 85]. Omega will become a backup system for GPS.

B. INCORPORATION OF GPS INTO AUV NAVIGATION

The inclusion of Global Positioning System (GPS) into AUV navigation has only been briefly examined before in [HUTC 90]. Here GPS is used infrequently to bound position errors of the inertial component of the system. The GPS data is coupled into an inertial unit data for computation. This computation is then used to update a Kalman filter. Which of the sensor based navigational components mentioned before to employ for AUV

navigation depends on many factors including the size of the AUV, power availability, area of mission employment, operating depth, and transit distance. Of course, more than one of the sensors described above may be employed in an AUV navigational system. The sensors, in many cases, are not mutually exclusive to each other or to GPS. However, no single sensor discussed can match the accuracy of GPS, which is on the order of 100 meters anytime, anywhere. Using a reference station can reduce GPS errors by at least a factor of ten [CLYN 91].

III. DETAILED PROBLEM STATEMENT

A. REQUIREMENTS

1. Mission

The SANS (Small AUV Navigation System) is to be a self contained navigational package that is to be vehicle independent and externally attached to the vehicle. The purpose for this package is to guide an AUV for a minimum of a 24 hour mission. This mission will consists of two phases; a transit phase and a mapping phase. During the transit phase (to or from the operational area) periodic GPS fixes will be obtained and based on this information the course and speed of the AUV will be adjusted to ensure that the AUV obtains the next waypoint or goal position on time. Dead reckoning using other components and the computer in the SANS will be used to maintain course between GPS fixes. Real time GPS fixes are expected to provide position accuracy to within 100 meters.

The mapping phase consists of the AUV trying to determine the location of objects of interests in the operational area. While operating in a mapping phase mode a depth cell, flexgate compass, and IMU or vertical gyro, along with GPS will provide accurate locations of objects of interest by post processing of this information. With post processing the locations of the objects of interests should be determined within ten meters rms or better.

2. Size and Weight

The size of the SANS package should be as small as possible, ideally no bigger than 150 cubic inches (not including power source) upon final design.The package should be elongated, streamlined and as hydrodynamic as possible. The package should also be neutrally buoyant or have slightly positive buoyancy. AUV power is a limited, thus the

smaller the size and the more streamlined the SANS package is, the less of a power drain on the AUV it represents.

3. Power

The SANS package shall carry its own power supply. This power supply should be sufficient enough to power the SANS for an mission duration of 24 hours of which up to four hours would be locating objects of interest during the mapping phase.

4. Platform Independent

The SANS should be an externally mounted package that is vehicle independent. Communications between the SANS package and the host vehicle could be through standard central processing unit (CPU) communications ports such as RS232/422 with a physical connection. Fiber optics could be another type of physical connection between the SANS and the vehicle. Non physical connections could include optical or sonic connections. The advantage of the latter two types of connections is that no physical breach of the hull is required although they may be more difficult to implement than a well known standard such as the RS232.

5. Development Platform

a. Naval Postgraduate School AUV Model Ii

Naval Postgraduate School AUV II (NPS AUV II) was launched on June 15, 1990. The NPS AUV II is six feet long, neutrally buoyant, and displaces 387 pounds. It has an operational time of two to three hours and a maximum speed of two to three knots. It has a turning diameter of less than 18 feet. The AUV has an aluminum hull and is powered by lead-acid batteries. Control surfaces include twin counter-rotating 4-inch propellers and eight plane surfaces as shown in Figure 1. The computer system consists of a Gespac computer with a Motorola 68030 processor and a two megabyte RAM card and uses OS-9 for the real time operating system [BRUT 91].

The NPS AUV II is solely operated in a swimming pool environment but still represents an ideal platform for general AUV research including the testing of GPS/INS integration into AUVs. To date over 50 research papers and theses have been involved with NPS AUV II. The first wet test platform for the SANS will be the NPS AUV II.

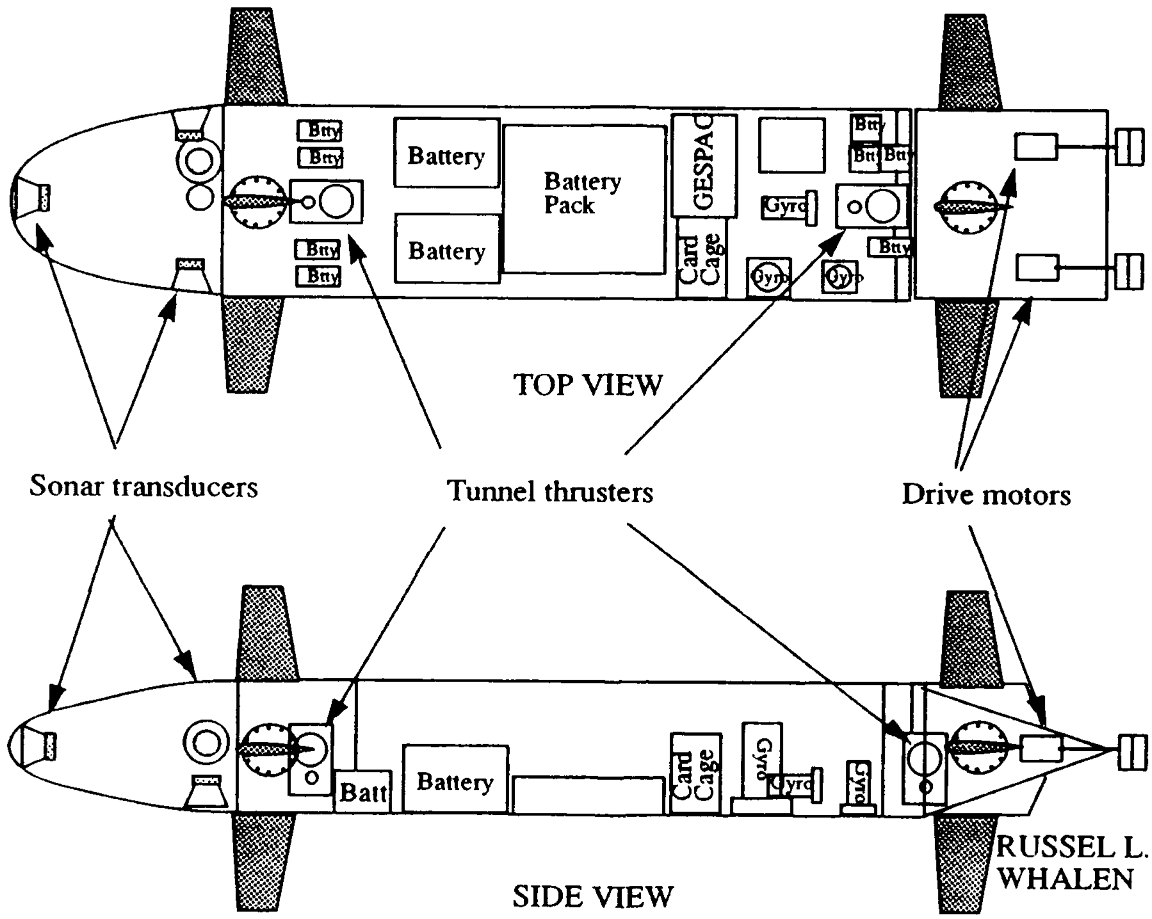

Figure 1: NPS AUV Model II Top and Side View Schematic

IV. GLOBAL POSITIONING SYSTEM

A. INTRODUCTION INTO GLOBAL POSITIONING SYSTEM

1. Satellites

The Global Positioning System (GPS) [WELL 87], [JANI 80], [HURN 89] is a satellite based navigational system that provides the most accurate open ocean navigation available. When completed, GPS will consist of a constellation of 24 satellites. Each satellite will be placed in high earth orbit (approximately 10,900 miles), which gives the satellites a period of 12 hours. Observing four or more satellites provides position and velocity in all three directions. By observing three satellites, two dimensional position and velocity may be computed. Currently the GPS constellation contains 16 satellites and the complete constellation should be in place by 1993. At that time, at least four satellites will be continuously observable from anywhere on the surface of the earth. Thus, world wide three dimensional coverage will be available. World wide two dimensional coverage is now essentially available.

2. Ranging

GPS navigation is based on satellite ranging. Basically, the distance from the location on earth to a satellite is measured.The GPS system determines distances by timing how long it takes a signal from a GPS satellite to reach a receiver. This is accomplished by having the receivers and satellites both produce the same set of digital codes. Upon receiving the GPS signal, the receiver compares it to its own code and uses the offset between the two codes to determine the time it took for the signal to travel from the satellite. Multiplying this time of flight by the speed of light gives the distance to the satellite. Four satellites are required for a 3-D fix because the receiver clock error must be determined. Three satellites can be used to find a 2-D position if altitude is known.

The distance between a GPS satellite and a receiver is not enough to determine the location of the receiver; it has to know, as well, the position of the GPS satellite. To determine the position of a satellite in real time, the satellite broadcasts parameters of a model of its motion. This is called the "broadcast ephemeris". Each broadcast ephemeris is only good for navigation for a few hours (nominally six hours). The ephemeris must be obtained from each satellite as it rises to use its data in a real time solution. As a result, a GPS antenna must be exposed for a period of 30 seconds to 60 seconds once every few hours to update the ephemeris data.

As a result of the 10,900 mile high orbit and the period of 12 hours for each of the GPS satellites; each of these satellites passes over one of the five Department of Defense monitoring stations twice a day. The stations precisely measure the altitude, speed and position of the satellites. Any variations in the ideal values are called "ephemeris" errors. The errors are fed into a model and uploaded to the satellites at least once a day.

3. Timing

Time is extremely accurate on the GPS satellites. Time is kept by the use of an atomic clock on the satellites. However, the accuracy of the GPS receivers is not as good and may vary from receiver to receiver. This problem is solved when four satellites are visible at all times. With four satellites a bounding box around the true location will be generated. The receiver, by applying algebraic algorithms based on four equations and four unknowns is able to accurately determine its own clock offset and apply a correction for that offset. As a result very accurate 3-D position information is provided when four or more satellites are available. Even atomic clocks may be subject to slight inaccuracies. However, the DoD monitors and adjusts theses clocks to keep them as accurate as possible.

4. Multipath

A signal may actually bounce off of objects and this reflected signal is received by the receiver thus adding great inaccuracies in timing and distance calculations. However, modern receivers are capable of mitigating errors due to multipath by advanced signal processing capability.

5. Geometric Dilution Of Precision

The relative angle in which the individual satellites are in relation to the receivers may compound all of the previous errors mentioned before. Simple geometry dictates that the greater the angle between satellites the better the location determination. Some older receivers use to only look at the first four satellites they have obtained. In this case Geometric Dilution of Precision (GDOP) was a problem. However, modern receivers will look at all visible satellites and perform optimization internally to minimize the affect of GDOP.

6. GPS Codes

GPS signals are very low power spread spectrum signals. The signal is generated by modulating a pseudo-random sequence of +/- 1's onto a carrier. The Department of Defense (DoD) can control access to the system by altering the codes. Currently, there are two main forms of the pseudo-random codes: the Clear Acquisition (C/A) code and the Precise (P) code. The C/A code is for civilian use, whereas the P code can be encrypted for only military use. The accuracy may be degraded by the DoD through Selective Availability (S/A). S/A creates a random clock error in the satellites, denying accurate use of GPS to all but those receivers with the cryptographic capability. Use of the P code, and removal of S/A, when encrypted, is available only to authorized military users.

7. GPS Signals

GPS signals are broadcast in two main frequencies: L1 and L2 at 1575 Mhz and 1227 MHz respectively. L1 is the primary signal that carries both the C/A code and the P code. L2 carries only the P code and is primarily used to remove propagation effects of the ionosphere from the ranges. GPS signals travel at the speed of light in a vacuum. However the speed of these signals as they head to earth are affected by the earth's ionosphere. The ionosphere is a region extending 80 to 1000 kilometers above the earth made up of electrically charged particles. The ionosphere slows down the speed of the radio waves which causes an error in time and distance computations. To correct for these errors the GPS satellite broadcasts its signal using two different frequencies. Due to the difference in the frequency, the speed of the signals will be affected by the ionosphere differently. As a result, a sophisticated GPS receiver will be able to account for the error caused by the ionosphere by comparing the arrival time of the signals associated with the independent frequencies. These ionospheric errors can be up to 30 meters. Because the C/A code is present on only one of two frequencies, use of a C/A only system leaves this ionospheric error in a navigation solution. However, it can be effectively removed for ranges up to a few hundred miles using a reference station [COCO 90]. The lack of an ionospheric correction is the major operational difference between C/A and P code receivers.

The error caused by a neutral atmosphere is from two to six meters. This error, however, may be modeled. The error due to water vapor in the atmosphere makes up about ten percent of the neutral atmosphere error and is much more difficult to model.

By DoD policy, S/A is on at a level that allows the GPS code to provide a horizontal accuracy of 100 meters (two standard deviations) in real time. With the use of a reference station the accuracy provided by both the C/A code and the P-code can be greatly improved. Table 1 provides a summary of expected accuracy. As it can be seen the status

of whether S/A is on or off can greatly affect the accuracy provided by a stand alone GPS system.

TABLE 1: POSITIONING ACCURACY OF GPS

	S/A on	S/A off
Stand Alone	100 meters	16 meters
Differential	2 - 4 meters	2 - 4 meters

GPS positioning solutions may be classified in several different ways including: real time or post processing, static or dynamic, and absolute position or relative position. Real time solutions may be derived directly from a single receiver or differentially from two or more receivers. A differential solution involves placing a receiver at a known location. Another similar receiver is placed at an unknown location. A GPS fix is taken at the known location and the error in measurements or error in the position between the GPS fix and the known location may be applied to the receiver at an unknown location. This technique may be applied in real time, requiring communication between the receivers, or at a latter time in a post processing phase. Differential GPS may also be used in both a static mode (a stationary platform) and in a dynamic mode (a moving platform). Relative GPS simply means determining the relative position of one receiver in relation to another.

B. GLOBAL POSITIONING SYSTEM RECEIVERS

Obviously, what is important to the end user is his position. Although a military receiver can provide greater real time, stand alone accuracy, it requires crypto keys and proper authorization. As a result, the rest of this thesis will only be concerned with civilian navigation receivers. This usually implies C/A code, single frequency receivers.

A GPS receiver may be continuous or switching. A continuous-tracking receiver has four or more dedicated hardware channels. Each channel tracks a single satellite and the satellite signal is continuously available. In a switching receiver one (or very few) hardware channels are available. Each channel samples two or more satellite signals. The switching involved in a receiver of less than four channels limits the accuracy of the dynamic positioning information because the satellite signals are not being received and processed at the same time. Due to the development of VLSI technology with multiple channels, five to 12 multichannel receivers will dominate this market. Therefore only multichannel receivers will be discussed. Although only four tracked satellites are needed to provide a 3-D position solution, the more satellite signals that are received and processed in real time, the quicker and more accurate is the solution provided.

One aspect that makes the use of GPS in AUV navigation possible is the advent of single board GPS receivers or engines. These are small, low weight, and in general low power. In addition, GPS engines are highly capable. GPS engines are available from at least five manufacturers. With a single board GPS engine, the user will have to supply the power and the interface. The interface, in most cases would be a standard RS 232/422 interface which should present little or no problem in interfacing with the AUV mission or navigation system computer. The cost of these single board GPS engines varies with the complexity and capability of the receiver but in general runs from $500 to $3,000 [ARRA 90].

C. TEST RESULTS

1. Receiver Selection

Due to cost and availability, only commercially available, off the shelf, GPS receivers were considered for this work. An initial look at available receivers showed the Globos LN 2000 F SEL (SEL) receiver to be very promising for AUV employment because

of the advertised fast satellite acquisition times. This SEL receiver is a C/A code, six channel, single frequency receiver. This receiver was put through extensive tests. The purpose of these tests was both to evaluate this specific receiver and the feasibility of incorporating GPS receivers, in general, into AUV navigation.

2. Test Set Up

Since just a GPS engine was to be used for the SANS; the company designed interface was not employed. Instead a junction box was built that allowed the GPS engine to communicate to a computer via the RS232 port and a communications program named GEORGE [CLYN 90]. The SEL receiver had several modes that could be selected. The mode selected determined the type of information provided as well as the baud rate, parity, number of data and stop bits for the selected mode. The different types of information that could be provided includes the PVT (Position, Velocity, Time) message, NMEA 0183A (National Marine Equipment Association) message, Nav String (Navigation String) message, and the Raw satellite data message. The mode was selected by a junction box that provided an interface to the *J2 connector*. The J2 connector is a Cannon D-subminiature, 25-pole jack. The J2 connector contains three configuration discretes d1, d2, d3, as well as power and ground. By wiring these pins to a junction box that contain high/low select switches for d1, d2, and d3 the desired mode could be selected. GEORGE provided the communications software for the computer. The junction box also contains a momentary switch that was normally closed and an on /off switch. Both of these switches acted as interrupts between the power source and the GPS engine. The antenna for the GPS engine was placed above all obstacles in the immediate area limiting the possible introduction of multipath errors.

The type of data collected primarily consisted of the Nav String data. Only one type of information could be collected at a time. The Nav String data contains the latitude, longitude, and height for position information. A figure of merit is provided with each data

string. The figure of merit is a confidence factor provided by the receiver to indicate the quality or reliability of the solution. The Nav String data also provides a list of the satellites tracked, and the signal to noise ratio on each satellite. The signal to noise ratio is an indication for the satellite signal strength. In addition, the Nav String data also displays which satellites have valid ephemeris and which do not.

At first data concerning how long it took the receiver to develop a good solution from a cold start with the receiver off for several hours and no valid information existed was collected for evaluation. However, this information upon further examination of the project requirements, proved to be not that useful. It is a safe and valid assumption that before an AUV is launched the GPS engine operation would have been validated and all possible information that would aid in acquiring satellites and determining a navigational solution would be provided to the engine. What was of critical concern for an initial evaluation of a GPS receiver is that the receiver be up and operating and providing valid information before commencing with the required tests.

Given the nature of AUV operational employment, an important consideration for a GPS receiver evaluation is its operational characteristics with intermittent power supply. The basic test methodology consisted of a simulated periodic surfacing of an AUV. This was accomplished by turning the power on for the GPS engine for a simulated surfacing and turning the power off for a simulated submerging. The surfaced time period was set at 0.5 minutes for the purpose of these tests. The simulated submergence times (power off times) consisted of 0.5 minutes, one minute, two minutes, four minutes, and eight minutes. Ten simulated surfacings were done per test run. There were three or four

test runs (30 - 40 observations) for all cases except for the eight minute off case for which there were two runs. Table 2 provides a listing of the simulated surfacings.

TABLE 2: LIST OF POWER OFF TIMES IN MINUTES, AND NUMBER OF TEST RUNS, OBSERVATIONS, AND SIMULATED SURFACINGS

Power Off Time	Number of Test Runs	Number of Observations per Test Run	Total Number of Simulated Surfacings per Off Time
0.5	4	10	40
1	3	10	30
2	3	10	30
4	3	10	30
8	2	10	20

This testing methodology was used to determine how long the receiver could go without receiving signals and produce acceptable satellite acquisition and navigational solution times. At some off time there should be a break point (a power off time) that is too long for the receiver to consistently provide the information required in an acceptable surfaced time (on time) period. During the gathering of this data, four to six satellites signals were available.

3. Satellite Acquisition and Solution Time Test Results

The results based on the data analysis are not what was expected as shown by Table 3. The first data to be analyzed consisted of the time it took the GPS receiver to acquire at least three satellites when the off time period was 0.5 minutes. For this off time three or more satellites were acquired 80 percent of the time in ten seconds or less. For the

off time period of one minute it took less then two seconds for 80 percent acquisition. These results as well as the rest of the data sets are summarized in Table 3.

TABLE 3: ACQUISITION OF 3 OR MORE SATELLITES IN SECONDS

% Acquisition	0.5 min Off Time Period	1 min Off Time Period	2 min Off Time Period	4 min Off Time Period	8 min Off Time Period
50	3	2	4	4	2
80	10	2	8	7	12
90	13	3	12	14	22
100	27	5	20	17	23

The purpose of this table is to show over the whole of the data, for the acquisition of at least three satellites what required amount of time can be expected. Clearly the inconsistency that stands out in Table 3 concerns the 0.5 minute off period. As mentioned before there are four sets of data for the 0.5 minute off period. The inconsistency lies in two of theses sets. The other two sets provide the expected results of showing the receiver acquiring three satellites 100 percent of the time in two seconds or less. In order to answer why these two pair of sets differ a number of items must be looked at.

The Nav string data provides the signal to noise ratio of each satellite track, and whether or not a valid ephemeris exists for each satellite. In all four 0.5 minute off time cases at least four or more satellites were available with a high signal to noise ratio. Next item that was checked was whether or not any of the satellites were rising or setting during these four test runs. Rising or setting satellites were not a factor.

In other words no explanation based on the available information can be found for the inconsistencies of the 0.5 minute off period data sets. Other factors may be acting internal to the receiver that is not described in the receiver manual. Unfortunately further

testing of this receiver was not possible since it was only available for a limited period of time.

The rest of the data sets in Table 3 are much more in line with what would be expected although minor inconsistencies do exist. What can be taken from Table 3 is that in all simulated surfacings the SEL receiver acquired three or more satellites in 30 seconds or less. An important consideration in understanding the Nav String data is that this GPS receiver will output a Nav String at the rate of one second or less. From one Nav string to the next it may be possible and in fact has occurred that the number of acquired satellites could jump from one or two to four or five. The result is that on several occasions within a data set the time for three or more acquired satellites will be very similar to the time for four or more acquired satellites.The information for four or more satellites is provided in Table 4.

TABLE 4: ACQUISITION OF 4 OR MORE SATELLITES IN SECONDS

% Acquisition	0.5 min Off Period	1 min Off Period	2 min Off Period	4 min Off Period	8 min Off Period
50	15	6	6	16	5
80	----------	13	8	----------	12
90	----------	----------	12	----------	26
100	----------	----------	24	----------	27

As it can be seen only 50 percent of the time did the GPS receiver pick up four or more satellites in 16 seconds or less throughout the data sets. The empty cells signify that one or more of the sets did not acquire four satellites for the listed percentage within the 0.5 minute on time. For example, every data set for the one minute off period picked up four satellites at least eighty percent of the time. 134 simulated surfacings acquired four or more satellites out of the 150 total surfacings simulated. The same kind of inconsistencies are seen in Table 4 that were presented in Table 3.

The data sets to determine a navigation solution are the same data sets used to determine the acquisition time for three and four satellites. The solution times upon initial inspection of the data sets did not look good. In fact, out of the 15 total data sets only three of them showed navigational solutions in all of the ten test runs. Even worse six of the 15 data sets failed to have a navigational solution on even five or more of the test runs each. Table 5 provides these are other related results.

TABLE 5: TIME TO NAVIGATION SOLUTIONS IN SECONDS

% Acquisition	0.5 min Off Period	1 min Off Period	2 min Off Period	4 min Off Period	8 min Off Period
50	---------	24	21	24	---------
70	---------	29	23	25	---------
80	---------	---------	24	25	---------
90	---------	---------	---------	25	---------
100	---------	---------	---------	27	---------

Table 5 shows that only for the four minute off time period was a navigation solution provided within the 0.5 minute on time period for each of the simulated surfacings. The 0.5 minute and the eight minute off time periods did not even obtain a 50 percent solution rate. The results shown in Table 5 are counter intuitive. What was expected is that as the off times increased the time for solutions would also increase. One key point here is that the on time was only 30 seconds. A longer on time would generate more solutions.

Only 86 of the 150 simulated surfacings provided a solution within 30 seconds. An in depth analysis of the Nav string data was again conducted. A general tendency was if some of the satellites that were being tracked did not have a valid ephemeris then a solution would not be provided. However, this tendency was not consistent throughout all of the data. There were cases where the receiver provided what it said was a valid solution but showed all satellites with in invalid ephemeris.

At this point some conclusions about the receiver, its performance and the test methodology employed can be made. First, the 30 second on time period was probably not long enough to fully evaluate what was happening. Second, clearly there is internal receiver processing that is not explained in the receiver manual. Unfortunately, further investigation of this receiver was not possible due to the limited available time. Third, no break point was found for up through eight minutes off. In essence the 150 simulated surfacings represent one data set as a whole as opposed to five separate sets based on the off times. As a result the 150 simulated surfacings will be analyzed as a single data group.

Table 6 represents probability distributions, at the listed percentages for satellite acquisition and navigational solution times. In summary, every simulated surfacing acquired three or more satellites. 134 of the 150 simulated surfacings acquired four or more satellites; and 86 of the 150 simulated surfacings provided a navigational solution in the 30 second on time.The acquisition rate for both three or more satellites and four or more satellites was outstanding. It is important to understand that the number of solution would have increased with longer on times.

4. Solution Accuracy Test Results

To determine the accuracy of the real time solutions, the GPS antenna was placed above an accurately surveyed site, so that its true latitude and longitude were precisely known. These were compared to the latitudes and longitudes provided by the GPS receiver and then the errors in latitude and longitude were generated. Figure 2 is a plot of these errors. As Figure 2 shows the greatest horizontal error was about 115 meters. The 50th percentile for the horizontal errors is 30 meters, and the 90th percentile is 80 meters. Table

7 shows the average, median, and standard deviation of the latitude errors, longitude errors, and horizontal or position errors.

TABLE 6: CUMULATIVE PROBABILITY DISTRIBUTION FOR THE TIME TO ACQUIRE THREE OR MORE SATELLITES, FOUR OR MORE SATELLITES, AND NAVIGATION SOLUTION IN SECONDS

% Acquisition	3 or More Satellites	4 or More Satellites	Navigation Solution
50	2	5	26
60	2	7	> 30
70	3	10	> 30
80	4	13	> 30
90	9	> 30	> 30
100	27	> 30	> 30

Despite the earlier stated inconsistencies an initial conclusion can be drawn about the use of this GPS receiver for the AUV navigation. So far, it appears to meet the minimum required objectives for the acquisition of three or more satellites in 30 seconds or less as well as providing a navigation solution in 30 seconds or less 57% of the time. Perhaps more encouraging is that this receiver does indicate that off the shelf GPS engines may be suitable for employment in AUV applications.

Although the SEL receiver was tested under an unusual operational condition, i.e., intermittent power supply to the receiver, the test results show that the accuracy of the real-time positional solutions confirmed the DoD policy, an accuracy of 100 meters in real time while S/A is on. The SEL receiver designed for civilian use does not have an ability to decode the correction for S/A; nevertheless, the accuracy from this test is very good for real time navigation compared with those available through any alternative open ocean positional devices.

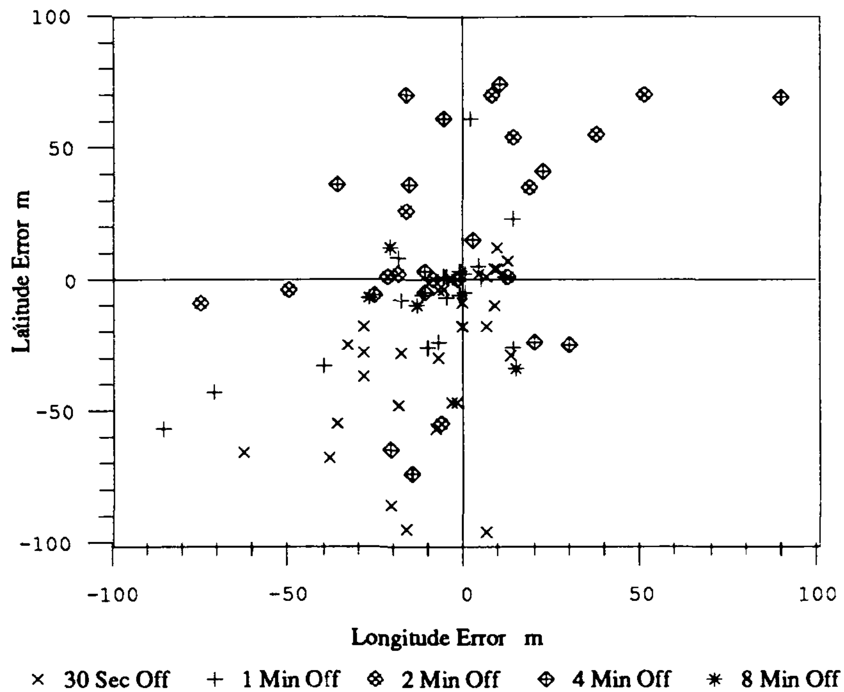

Figure 2: Latitude and Longitude Error Distribution in Meters

TABLE 7: AVERAGE, MEDIAN, AND STANDARD DEVIATION FOR POSITION ERRORS

	Latitude Error	Longitude Error	Horizontal Error
Average	-7	-7	36
Median	-4	-5	28
Standard Deviation	37	25	29

V. INERTIAL NAVIGATION SYSTEMS

A. INTRODUCTION TO INERTIAL NAVIGATION SYSTEMS

Inertial navigation systems(INS) senses acceleration. This acceleration is integrated twice yielding position of the vehicle. Two coordinate systems are associated with INS earth coordinate system, in other words relative to the earth, and body coordinate system which is relative to the vehicle. The first integration of the sensed acceleration may be in either coordinate system but the second integration must be in earth coordinate system to establish the location of the vehicle. There are in general two classes of inertial systems: stable platform and strap down.

1. Stable Platform

Stable platform inertial navigation systems carry three single-axis accelerometers aligned to measure acceleration directly in earth-fixed coordinates. As a result there is no need for coordinate conversion to the earth-fixed coordinates. Although stable platforms are high precision navigation systems they are not suitable for AUV employment due to size, weight, amount of space required and of course the associated costs [MCGH 92].

2. Strap Down

The primary difference between stable platform and strap down systems besides size, weight, space required, cost, and accuracy (which are all significantly less for a strap down system) is that a strap down is rigidly mounted to the vehicle. In a strap down system a Inertial measurement unit (IMU) contains three angular rate sensors and three linear accelerometers. Strap down systems are becoming smaller, lighter, more accurate, and less expensive every year. Only strap down systems offer viable option for small AUV incorporation.

a. Angular Rate Sensors

There are five classes of angular rate sensors.

(1) Rotating gyros. Rotating gyros have a rotating mass and represent the oldest technology for angular rate sensing. They are characterized by high cost, high power, and relatively low accuracy. Rotating gyros are in general a poor choice for AUV navigation.

> A pertinent example is the three-axis rate gyro package currently employed by the NPS Model II AUV. This component is roughly the size of the entire navigation package proposed...requires more power than will be available, possesses an unacceptable drift rate...and has a lifetime of only about 200 hours.[1]

(2) Fiber optic gyros. Fiber optic gyros measure rotational rate about a single axis. A coil of optical cable is used to provide a long path. The changes in the travel time of the laser light is induced by angular rotation of the vehicle. It is this change in the speed of light that is measured. Fiber optic gyros, in general, are relatively inexpensive. Litton is developing a complete fiber optic IMU system for missiles called LN-200. This package weighs 3 pounds and is 75 cubic inches. It requires 25 watts. When in production (in 1993) it is expected to cost about 15K. Table 8 provides Litton's advertised performance. Both incremental velocity and incremental rotation are available for outputs The noise for the accelerometer was not available. [MCGH 92]

1. [MCGH 92 p. 3].

TABLE 8: LITTON LN-200 IMU PERFORMANCE

	Gyro	Accelerometer
Range	1000 deg/sec	40g
Bias	1 deg/hr	200μg
Scale Factor	100ppm	300ppm
Output	$\Delta\theta$	ΔV
Noise	$0.03\text{deg}/\sqrt{\text{hr}}$	

(3) **Ring laser gyros.** Ring laser gyros operate on the same principle as fiber optic gyros. However, instead of detecting the difference of the speed of light in a fiber optic cable, a triangular or quadrilateral shaped rigid glass body with mirrors at each corner is used. Honeywell is developing a triangle ring laser gyro for incorporation into a torpedo that is smaller then the LN-2000 with equal or superior advertised performance characteristics and about the same in cost.

(4) **Vibratory rate sensors.** The key component of a vibratory rate sensors is a tuning fork. When the fork is rotated a coriolis developed in the base of the fork. The magnitude of the generated torque is proportional to angular rate. Systron Donner QRS sensor is designed for aircraft and missile applications. This sensors is very small less than 1 cubic inch and requires only 0.8 watts. However, the drift rate is sensitive to

temperature, 0.01 degree/second/degree celsius. An initial estimation showed that this drift rate appears too great for SANS employment [MCGH 92].

(5) **Fluidic Rate Sensors.** Fluidic rate sensors are similar to vibratory rate sensors in that they also make use of coriolis forces. The deflection of a stream of helium gas caused by angular rotation of the nozzle is measured. These systems are small and inexpensive but their output linearity is around one percent of full scale making them unsuitable for the SANS.

b. Translational Acceleration

All accelerometers contain a proof mass. A proof mass is a rigid body and is fixed in a position. This mass is used to sense acceleration. The important point here is that accelerometers do not sense acceleration due to gravity. As a result accelerometers must be linear with a known scale factor and a small offset. In general IMU system should have an accuracy of a few parts in 10,000. A closer look at this accuracy with some simplified error bounding gives a better understanding of what this accuracy means. The magnitude of gravity is 9.8 meters per seconds squared which means an acceleration error of 0.00098 meters per second squared. By bounding this error by making the assumption that it is a constant bias then the time required to produce a five meter error is [MCGH 92],

$$1/2at^2 = \frac{0.00098}{2}t^2 = 5 \qquad \text{meters} \qquad (1)$$

and

$$t = \left(\frac{9.8}{0.00098}\right)^{1/2} = 100 \quad \text{seconds.} \qquad (2)$$

The fact that after 100 seconds a five meter drift error occurs shows that periodic GPS fixes and accurate error analysis are needed to determine AUV location.

c. *Velocity Sensing*

There are three basic methods for measuring velocity of an AUV. These are: doppler sonar, correlation velocity log sonar, and water speed measurements [HUTC 90], [STEV 90], [CAMP 91], [MCGH 92]. If velocity measurements are more accurate then IMU measurements then the velocity measurements could be used to improve the position location of an AUV. However, the doppler sonar and correlation velocity log sonar although employable in AUVs are too large and require to much power to be employed in the SANS. The speed water measurements are subject to currents and thus not very accurate. Clearly this area needs further investigation but one approach that does seem to hold promise is, if the AUV dives or ascends in a constant angle, estimating velocity, v, through depth measurement using the relationship [MCGH 92],

$$\dot{z} = v \sin\theta \qquad (3)$$

where θ is the dive angle, and z the depth. As a result:

$$v = \frac{z}{\sin\theta} \approx \frac{\dot{z}}{\theta} \ . \qquad (4)$$

VI. SYSTEM CONFIGURATION

A. OVERVIEW

The basic system design for the SANS is presented in Figure 3.

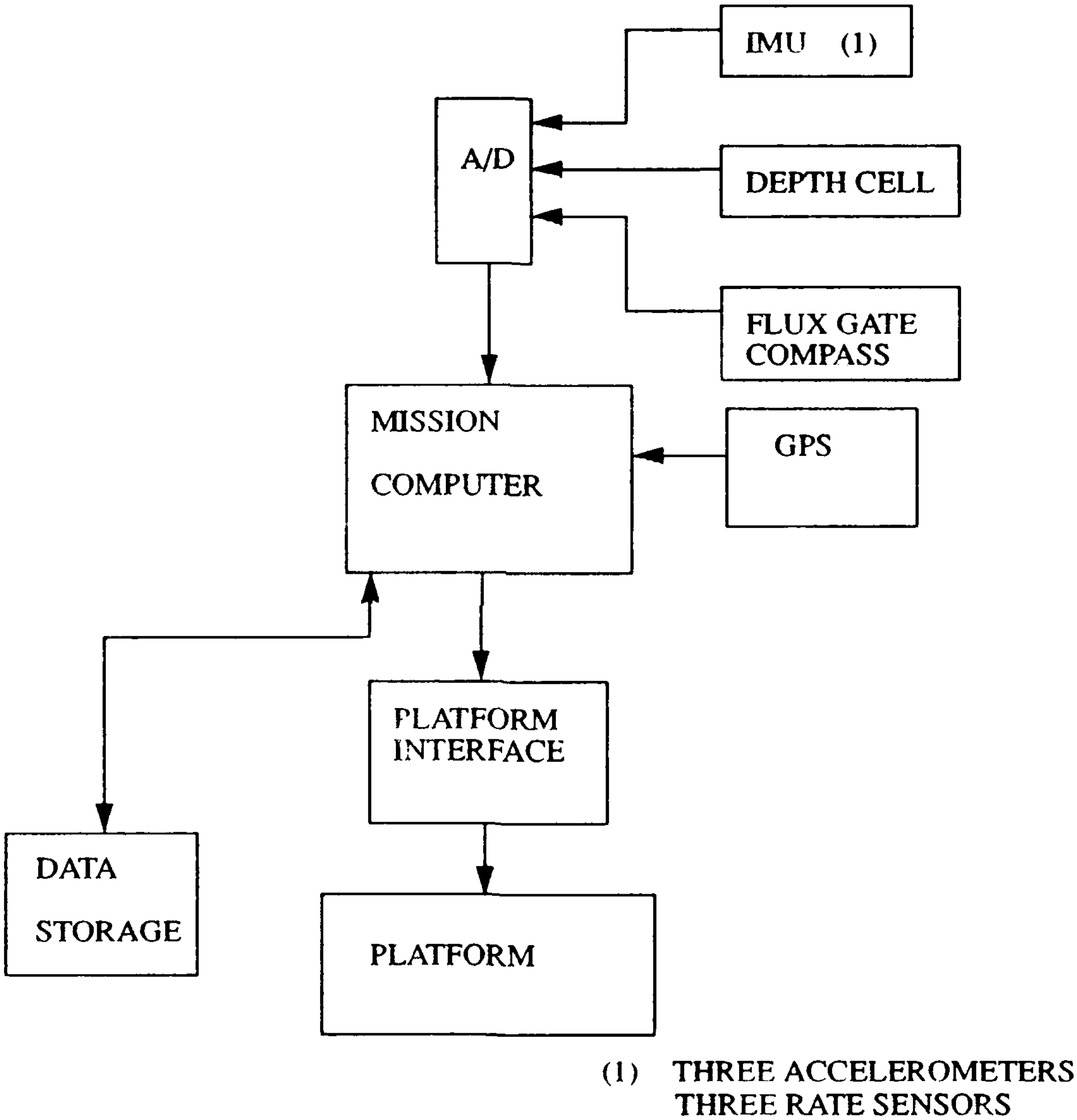

Figure 3: Hardware Block Diagram for SANS

As it can be seen the other major component besides the IMU and the GPS engine is the computer system.

1. Computer System

The general requirements and constraints that govern the other components of the SANS logically apply to the computer system. The computer system must be as small in size as possible with as low power consumption as possible. In addition, it clearly must be powerful enough to handle the assigned tasks and contain enough memory for the program, operating, and data storage. The best option would not include a disk or any type of secondary memory. A diskless system would save power and size. Like the rest of the SANS components the computer system should be comprised of off the self components as opposed to a specially designed system.

a. Configuration

A single processor system will make up the heart of the computer system. At this time there appears to be no real need for a multi-processor system, concurrent, or parallel processing. A single processor system provides the advantage of less space and less power requirements. A power regulator will be required to ensure that the Central Processing Unit(CPU) will have a constant power supply. The computer system should contain at least two megabytes of Random Access Memory(RAM). This is based on a 10Hz sampling rate for 10 bytes per sampling for a total of 4 hours of data collection. This sampling rate would yield about 1.5 megabytes of data. The program and operating system would be stored in ROM.

b. Inputs

The computer system with the CPU will have to be able to process and store data from an IMU which will consist of three accelerometers and three rate sensors, a depth cell, and a compass. All of these components are analog. As a result an Analog to Digital

converter (A/D) will be required. There is no requirement for the A/D to be part of the computer system. In fact it could be a stand along component. However, there are advantages to having the A/D as part of the computer system. These include size and interface considerations.

In other words if the A/D is integrated component wise into the computer system, less space will be used up and a better interface between the A/D and the CPU would exist.

c. Power Considerations

Other than simply stating that the less power the better, there are other factors that play into the power equation for the computer system. Demand on the CPU is going to be relatively light during the transit to and from the mission area. In essence, all that will be required will be for the computer is to produce a new heading command and speed command for the AUV to obtain the next waypoint every time a GPS fix is taken. A GPS fix will only be taken at intervals not to be less than three minutes. Given this light processing load a CPU with varying clock speed becomes extremely beneficial. The reason is that power consumption of a microcomputer system is roughly proportional to its system clock speed. If a low clock speed of four or eight MHz could be used for the transit phase and a greater clock speed for the mission area phase then significant power may be saved.

With only one clock speed available then that speed and the resulting power consumption will have to be great enough to handle the mission area phase and as a result the transit phase would be using more power than is required. With dual mode power then total power consumption for the duration of the trip would be greatly reduced. It is important to remember that one of the objectives of this package is to have a life of 24 hours. In other words to have enough power for a mission of 24 hours or longer.

The desired power requirements of the CPU without the RAM or the power regulator or the A/D converter is a max of one watt. As the different components are

integrated into the mission computer this power limit of one watt will obviously rise. The key question seems to be what would be more power efficient: A fully integrated computer system board or one made up of separate components. The former offers the best configuration with respect to power. The reason for this is simply that a system designed to be low power from the start and fully integrated and compatible will be more efficient than one made up of different components.

d. CPU Computational Power

Due to the relatively light computational requirements for real time processing by the SANS, a V20, 80C88 compatible processor and an eight bit bus is all that may be required. The concern for this type of a processor is that it does have a lack of future growth in tasking complexity or increased real time processing. The main advantage is that less power would be required.

Due to this lack for potential growth a 286 or ideally a 386 based CPU would represent a much more logical choice. However, has with all components, power and size will be the driving factors.

e. Processing

All processing will be done in a sequential manner, and only one processor, 80C88 compatible, will be used. Therefore the Microsoft Disk Operating System (MS-DOS) is the operating system of choice. In this type of computing environment DOS in essence will function as a real time operating system. The advantage to using DOS is that it is widely available and well known.

The language of choice is ADA. The advantages of ADA is its portability, demanding input/output requirements, strong typing, and error handling capabilities. Of course there is also a Department of Defense requirement that all embedded deployed system be in ADA. Since this project is being developed with a view toward becoming a

deployable system, the use of ADA from the beginning would prevent an unnecessary transition at a latter date. The language, however, is not the overriding consideration. Power and size will drive the computer system design. Most of the work, however, will be done in post processing on a portable workstation giving much more computational power and flexibility in language choice. The primary purpose of the embedded software in the SANS is to use GPS and the compass to navigate to and from the mission are^ on time. Once in the mission area, the software will record and store data from all sensors when objects of interest are found. It is this information that will be post processed.

2. Depth Cell

The depth cell must be small, low power and accurate up to a depth of 500 feet to meet the requirements for the SANS package. The linearity of full scale should be as small as possible and certainty less then 1 percent.

3. Compass

Again the same overall requirements for the other components also apply to the compass: low power, size, weight, and has accurate as possible. The compass should have an accuracy of no more than +/- 0.5 degrees. An additional issues is that the compass be able to account for the magnetic signature of the SANS package and the host platform.

4. A/D Converter

An A/D converter is required for the outputs from the compass, depth cell, and IMU system. The A/D converter then provides these outputs to the CPU. Due to this configuration what is required is an A/D card that is compatible with the CPU to prevent interface problems. Again, the A/D converter should be as small and low power as possible with the capability of handling several outputs from different components.

5. Power Regulator And Interfaces

The power regulator and interfaces are not shown on Figure 3. A power supply regulator should be used to ensure that all the components would have a constant power source that meet the needs of the individual components. The regulator should be at no less than 85 percent efficiency. The regulator should also be computer controlled so that the turning on and off of some components when required could be easily handled.

The platform interfaces and devices are standard RS232 interfaces. However, fiber optic, optical, and sonic interfaces also [illegible] possibilities for the platform interface.

B. SYSTEM CONFIGURATION

After extensive surveying of the requirements of the SANS and the requirements of the individual components of the SANS, an initial system configuration is proposed. The components proposed for the make up of the SANS all individual meet the minimum requirements to make this system possible. They certainly meet all requirements for a prototype bread boarded systems which would be the next phase of the SANS project. It is important to remember that literally new technologies and products are coming out every week and in all cases the trend is to smaller, faster, more accurate, and more capable. The configuration proposed here is simply the initial cut on the SANS system design.

1. Gps Receiver

The GPS receiver suggested is the GLOBOS LN 2000 GPS engine by SEL. Extensive test and evaluation was done on this receiver. The satellite acquisition times and times to a solution as well as the stability of the solutions are all minimally acceptable for the initial design. The test and evaluation of this receiver clearly demonstrates that off the shelf civilian use receivers will be adequate for this project.

2. IMU

The preferred IMU is the Litton LN- 200 IMU. As mentioned before this IMU is relatively small, light weight, low power, and low cost. The advertised accuracy meets initial SANS development requirements. This IMU is the best overall choice for initial SANS development.

3. Mission Computer

The mission computer proposed is an Octagon Systems Corporation 5012 PC Control Card. This is an 80C88 board rated at 4.7 or 12 mhz. This board carries up to two MB of DRAM and is EPROM capable. It runs DOS 3.31 and has a watchdog timer that will reset upon a program crash. This is software enabled. The clock speed may be slowed down to conserve power during periods of light operational loads. The pre-mission program and the operating system DOS 3.31 would be loaded into the EPROM. The 2 MB of DRAM are believed to provide more than enough memory for data storage during the mission.

4. Depth Cell

The proposed depth cell is a pressure transducer by Celesco. Celesco manufactures the transducer currently in use in the NPS Model II AUV. The transducer for this application is the DP30 with a range of +/- 0.1 to +/- 500 psi which would provide for a depth of over 1100 feet. The linearity is +/- 0.5% of full scale. Celesco also provides a compatible low cost demodulator for the transducer.

5. Compass

The preferred magnetic compass is manufactured by KVH Industries and is the C100 Multi-Purpose Digital Compass. This compass has an accuracy of +/- 0.5 degrees and has an auto-calibration method that deals with the magnetic signature of the host platform.

6. A/D Converter

The proposed A/D converter is manufactured by the same company that produces the mission computer. The advantage to this selection is that the mission computer and A/D converter are compatible and would both fit in the same card cage if used. The A/D converter of choice is the 5710, a high resolution, low cost analog card. This card has up to eight differential channels for analog inputs and 19 digital I/O lines. The 19 digital lines are divided into one group of three lines, a second group of eight lines, and a third group of eight lines. In the first group all lines are outputs. The second group may be configured with four lines as inputs and four lines as outputs. The eight lines in the third group may be configured as all inputs or all outputs.

7. Power Requirements

a. Power Estimates

In order to estimate how much power would be required for the mission the mission itself has to be defined. It is projected that the SANS maximum mission duration will be 24 hours with 4 hours of operation in the survey area. Therefore the mission can be broken down into two phases. The first phase is the transit phase to and from the survey area. The survey area is the area to be searched for objects of interest. The SANS package is vehicle independent and will carry its own power supply. There are two ways to handle power allocation for the SANS package. The first way is to power up the entire package for the entire mission. The second way is to only power up the components of the SANS package when needed. Table 9 presents the component power configuration for the transit phase. As it can be seen from Table 9 the GPS receiver would not be powered all the time. By only powering the GPS receiver when required represents a significant savings in power. As it now stands the GPS receiver requires eight watts, much more than any other component.

TABLE 9: TRANSIT PHASE POWER REQUIREMENTS

EQUIPMENT	POWER (Watts)	100% ON TIME
DEPTH CELL	0.75	YES
CPU BOARD	2.0 (slow)	YES
FLUX GATE COMPASS	0.36	YES
A/D CONVERTER	0.35	YES
GPS RECEIVER	8.0	NO

The maximum power requirement for the transit phase is:

$$0.75 + 2.0 + 0.36 + 0.35 + 8.0 = 11.46 \approx 11.5 \quad \text{watts.} \qquad (6)$$

The minimum power requirements would be:

$$0.75 + 2.0 + 0.36 + 0.35 = 3.46 \approx 3.5 \quad \text{watt s.} \qquad (7)$$

Estimating the transit to total 20 hours and using the minimum power requirements for a duty cycle of 0.9 gives:

$$0.9 \times 20 \times 3.5 = 63 \quad \text{watt-hours.} \qquad (8)$$

Estimating the power regulator efficiency at 0.85 yields:

$$63/0.85 = 74.1 \approx 74.5 \quad \text{watt-hours.} \qquad (9)$$

Now by using the maximum power requirements, a duty cycle of 0.1, and a power regulator efficiency of 0.85 yields:

$$0.1 \times 20 \times 11.5 = 23 \quad \text{watt-hours} \qquad (10)$$

and

$$23/0.85 = 27.1 \approx 27.5 \quad \text{watt-hours.} \qquad (11)$$

Table 10 shows what components would be on during the mapping phase.

TABLE 10: MAPPING PHASE POWER REQUIREMENTS

EQUIPMENT	POWER (Watts)	100% ON TIME
DEPTH CELL	0.75	YES
CPU BOARD	2.5 (fast)	YES
FLUX GATE COMPASS	0.36	YES
GYRO	1.5	YES
A/D CONVERTER	0.35	YES
GPS RECEIVER	8.0	NO

Using the same type of assessments as before with the exception of the duty cycle provides the maximum power requirements of approximately 64 watt-hours. Total power required is simply the totals added up:

$$74.5 + 27.5 + 64 = 166 \qquad \text{watt-hours.} \qquad (12)$$

The average power of the 24 hour mission is 7.0 watts per hour and the peak is:

$$64/4 = 16 \qquad \text{watt/hours.} \qquad (13)$$

The important idea is that by minimizing the amount of time any given component is on significant power savings can be made. The CPU has two clock speeds 4.77 mhz and 12 mhz. When ever possible the CPU should be run at a lower speed. The power requirements listed in Tables 9 and 10 distinguish which speed the computer is running at fast or slow. These power estimates were based on company provided literature and were rounded up at very opportunity so a maximum estimation would be used when the actual power supply type required would be examined. Of course these values are component specific for the SANS package. Any change in the design, addition, deletion, or replacement of these components would require a recalculation of power requirement estimates. However, the power requirement estimates presented in this thesis believed to be somewhat accurate for the final configuration of the SANS and are certainly in the ball park.

b. Power Sources

The SANS package is to be vehicle independent and contain its own power source. One advantage to this approach is that the AUV would not have to be reconfigured

in order to ensure enough power is available for the SANS. With the SANS having an integrated power source there is one less connection between the AUV and the SANS. The integrated power supply increases the SANS platform independent feature and adds to the portability of the system.

Along with the advantages of the integrated power source there are major concerns. One concern is the weight and size of the power source. Clearly this is dependent on how much power is required. However, it is for certain the battery configuration will represent the largest weight and size component of the SANS. The SANS package will not just have to be big enough to house the power source, but it will have to be big enough to ensure that it is neutrally buoyant.

As for the batteries themselves, they may be rechargeable or throw-away. Which type to use depends on the capability in relation to power output, operating environment, and size and weight. Using 180 watts as total power requirements only represents the starting point.

Two battery types immediately stand out based on the operational parameters and energy density. They are Alkaline batteries and Zinc Chloride batteries. Table 11 provides a comparisons between these two types of batteries. Mercuric Oxide batteries and Silver oxide batteries offer an energy density of 50 Watt Hour/lb but have poor operational characteristics in low temperatures. Zinc Air batteries have an energy density of 150 Watt Hour/lb which is outstanding but requires atmospheric oxygen for operation.

TABLE 11: ALKALINE AND ZINC CHLORIDE BATTERY COMPARISONS

	Battery Type	
Characteristics	Alkaline	Zinc Chloride
Rechargeable	No	Poor
Volts per Cell	1.5 (D-Cell)	1.5 (D-Cell)
Watt Hour/lb	40	30-40
Watt Hour/ cubic inch	3	2-3

Since the Alkaline batteries are not rechargeable they will be more expensive to use for the SANS package. Other than that either of these two types of batteries should meet the power source requirements of the SANS package. The size of the battery pack consisting of either the Alkaline or Zinc Chloride batteries would be about five pounds of batteries. Using a sea water density of 8 pounds per gallon and 231 cubic inches per gallon yields

$$1 \text{ pound} / 28.9 \text{ cubic inches} \times 5 \text{ pounds} = 144.5 \text{ cubic inches.} \qquad (15)$$

In essence 150 cubic inches will be required for the power source which is as big as the rest of the SANS package. A possible configuration would be a two package system in which one package contains the battery pack with the other components of the SANS system in the other package.

VII. SANS EMPLOYMENT

A. TRANSITS

The SANS system represents an excellent method to employ GPS into AUV navigation for even medium transits of ten miles. The SANS system would be able to provide a GPS position to the AUV within 100 meters. For this point two approaches can be taken. The first is that either the SANS systems can provide just the position information to the AUV mission computer, and the mission computer would then calculate a new course and speed for the AUV to make the next waypoint or goal destination. The other approach would be to program the SANS system itself to provide the course and speed needed to complete the transit. Which approach to take would depend on the AUV employing the SANS system. The AUV on-board mission computer could also be programmed as to how often and under what circumstances a GPS fix should be provided from the SANS. Such criteria would be part of the mission planning phase and would include such incidents as a long deviation from course for obstacle avoidance, a failure or loss of the INS system, and simple periodic fixes. Before an AUV can conduct a mission it must arrive at the mission area or stating point. In many applications, especially military, this may involve a transit of some distance.

B. PRECISE OBJECT LOCATION

1. General Considerations

One of the primary functions of AUVs, in general, is to locate objects of interest under water. In order to successfully employ an AUV to accurately locate objects of interest it must be submerged. This, however, does not preclude the use of GPS in this type of high precision or detailed work. If the area of operation is shallow water 50 to100 meters of depth, two methods may be employed when an object of interest is found.

2. Baseline Design

One method involves continued submerged operation. Before the AUV submerges a GPS fix is recorded and an INS or other dead reckoning system is initialized. When the AUV submerges, it continually records navigation data. If objects of interest are found the AUV records the time of such events. Upon return, the GPS fix taken before the AUV submerged is differentially processed, and this data is fused with the navigational information to accurately determine the locations of objects of interest. The key feature is that the internal navigational system allows for continued submerged operation. How long the AUV will be able to stay submerged without a GPS fix depends on the drift rate of this inertial system. However, submerged times of five minutes or longer seem to be possible with new low cost, low power, small size INS systems now entering the market [MCGH 92]. Figure 3 titled Hardware Block Diagram for the SANS in Chapter VI, as previously shown, represents the configuration of the Baseline design.

3. Interim Design

Another method to compute the difference in position from a submerged object and a surface location of a GPS fix is to use a pop up maneuver that uses only inexpensive sensors[MCGH 92]. Depth change can be accurately measured with simple sensors. In addition, if the climb and orientation are measured to a degree or so, the true location can be determined. An inexpensive gyro could sense the climb angle and a compass the orientation. Figure 4 represents this method. Where Z is the depth, θ the climb angle, and H the horizontal distance to the object.

On a differential basis, the horizontal movement, ΔH, is just the depth change, ΔZ, times the cotangent of the elevation angle, θ,

$$\Delta H = \Delta Z \cot\theta \ . \tag{16}$$

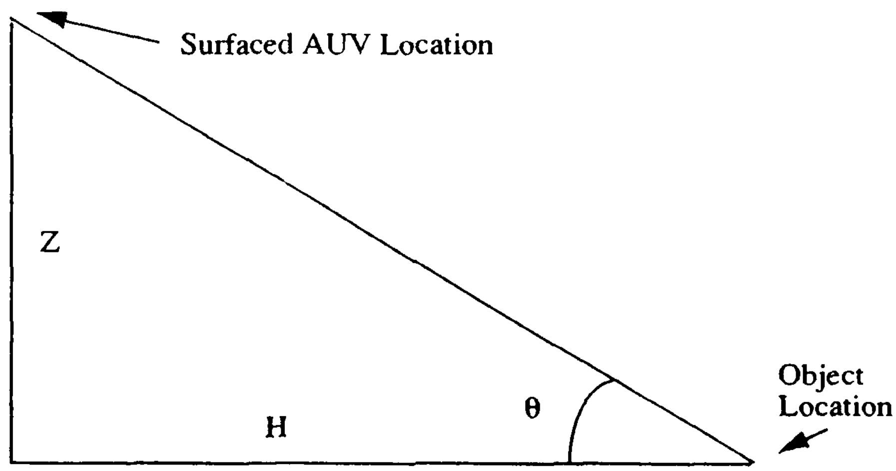

Figure 4: Object Location Diagram

These calculations are integrated in small increments. Due to the integration process random noise will be reduced. The systematic noise, with analysis of the system can be determined in the pre-mission planning. From Figure 4 it can be seen that the horizontal error is proportional to the cosecant squared of the average rise angle; that is,

$$\frac{dH}{d\theta} = -Z\csc^2\theta\,. \qquad (17)$$

Using equation 17, for example, if the AUV rises 100 meters at an average angle of 10 degrees, and the angle sensors all have residual systematic errors of 0.5 degrees, the horizontal position error would be about 30 meters. An ascent angle of 45 degrees leads to a 2 meter error. An important consideration is that the effect of currents on vehicle motion are not taken into account. If accurate knowledge estimations of currents are available before the mission there is no satisfactory way to account for these errors. Instead of a straight line ascent a spiral ascent could be used. However, sideslip would be unaccounted

for. Clearly further investigation of the pop-up method is required. Figure 5 represents the configuration of the Interim design.

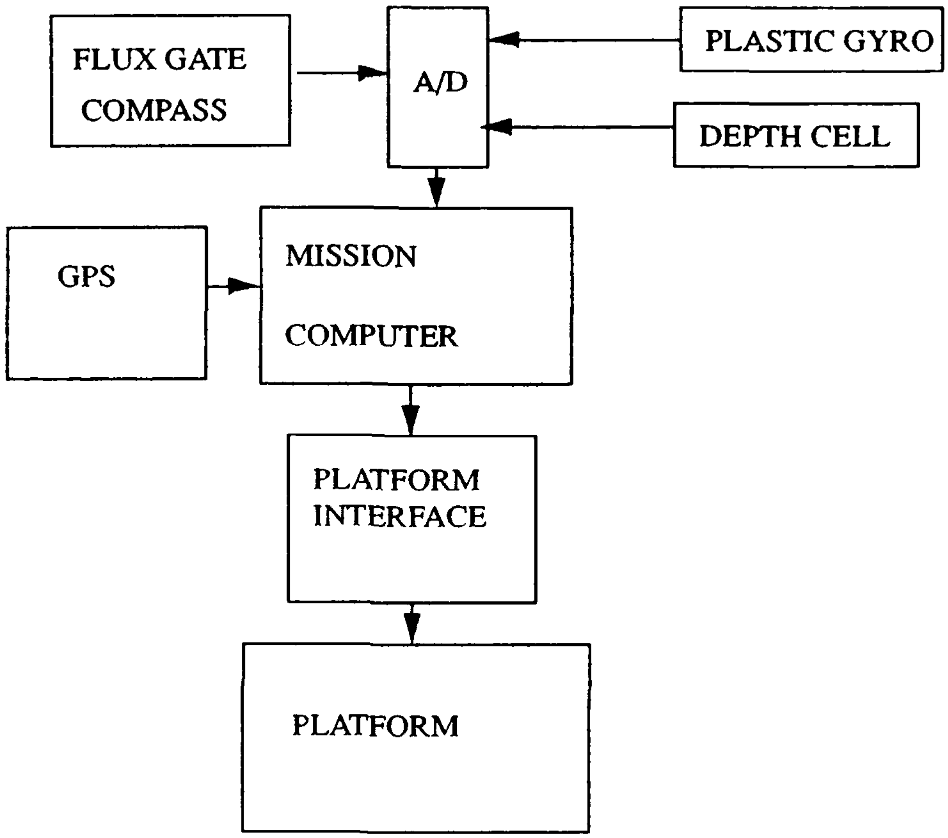

Figure 5: Interim Design

The only difference between the Baseline design and the Interim design is the use of a vertical gyro versus an IMU. The vertical gyro that will be used represents new technology developed by Gyration Corporation. This gyro is called the GyroEngine. The GyroEngine is a free spinning two-degree of freedom gyroscope. The height is 1.75 inches and has a diameter of 1.25 inches. The weight is 1.2 ounces and it only requires 0.1 watts. Angular resolution is 0.1 degree. The drift is, however, two degrees per minute with active torquing. This may prove to be unacceptable for the SANS Interim design. However, error

analysis is required. Angular range 360 degrees of yaw continuous, and +/- 80 degrees of pitch and roll. The GyroEngine supports RS232/422 interfaces.

The uniqueness of the GyroEngine lies in the way it is manufactured. It is a polycarbonate plastic that is injection molded. The motor control electronics are integrated into the inner gimbal. It uses optic sensors that provide a direct digital output. Given the small size, weight, low power, and the fact that it is low cost makes it a very attractive option for the Interim Design. Although accuracy may be somewhat questionable, this option is well worth pursing.

VIII. CONCLUSION

The SANS package represents an attractive system for AUV navigation especially in for transits of small duration and precise object location. As a minimum GPS easily can be incorporated into general AUV navigation with a real time position accuracy unmatched by any other method. By using a reference station or with post processing the accuracy could be improved to two to four meters.

The test results for the SEL receiver did show that incorporation of GPS into the SANS package or AUV navigation is definitely feasible. Of course GPS used for AUV navigation has the great disadvantage of having to have an antenna exposed clear and free of the water to receive the satellite signals. The other key component is the IMU system which will maintain the position of the AUV between the GPS fixes. The Litton LN -200 IMU seems to be the best suited for the SANS package. The mission computer should be able to handled all the SANS system components, software, and data storage requirements without using an external disk. An off the shelf small computer system can meet this requirement. The key issues with the other components are the same as with the SANS as a whole, low power consumption, small size and weight and as accurate as possible.

Power requirements for an envisioned 24 hour mission with four hours in the operating area comes to about 180 watt-hours. This requirement can be met by either Alkaline batteries or Zinc Chloride batteries at about five pounds. Five pounds of batteries would require 150 cubic inches of space to maintain neutral buoyancy. As a result a two package system is proposed: one package for the battery pack and another for the rest of the SANS components.

The SANS system is ideal for AUV transits and precise object location. Either of the two proposed designs can accomplish precise object location in shallow water. The first design is the Baseline design and the second is the Interim Design. The difference between the two designs is that the Interim design uses a plastic gyro instead of an IMU, and that

the vehicle will have to pop-up or surface when an object of interest is located. With the Baseline design continued submerged operation is possible for as long as the IMU can hold an accurate position. This is estimated to be in excess of five minutes. During the mission phase all information is post processed yielding accurate object location.

IX. FUTURE WORK

This thesis represents an initial cut for a system design for the SANS package. In fact, Two designs are presented. The next step involves further testing of a GPS engine to certify that solutions and satellite acquisition times are fast and accurate enough for AUV navigation employment. This testing needs to be automated through a computer so that data collection is easier and more accurate. The data for this thesis was collected by a human physical turning the GPS receiver on and off using a stop watch for timing.

A SANS system needs to be breadboarded for lab top study and analysis. This SANS prototype will represent the next step in the development of this project. With a lab top prototype the SANS component configuration may be verified and updated. Detailed error analysis may be conducted. System and random noise may be studied. The SANS programming may be started, and initial validation conducted. This prototype should be based on the Interim design due to the cost involved. Of course any work conducted on the Interim design is directly applicable to the baseline design.

After prototype testing and validation, then an Interim design prototype should be built with a goal of testing the design in operation with the NPS Model II AUV.

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